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THE ROLE OF SATELLITE ALTIMETRY IN CLIMATE STUDIES

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INTRODUCTION

Within the past decade, the variability of the climate and its consequences have been dramatically demonstrated by several events. The drought in the Sahel in the late 1960's and early 1970's, the failure of the Peruvian anchovy harvest, and the reduction of the Soviet grain harvests by drought in the early 1970's have all increased our awareness of climatic fluctuations. Direct effects have also been felt in the United States. In 1977, the eastern half of the U.S. was experiencing record-breaking cold temperatures and high snowfall while the west was besieged by drought. In 1978, however, precipitation was sufficient in the western U.S. to restore reservoirs and water reserves to normal levels.

This unexpected variability in the climate of recent years has resulted in a movement to better understand our climate both on the national and international levels. The 95th Congress enacted the National Climate Program Act in 1978 to establish a base for a vigorous and extensive National Climate Program, now in its formative stages. At the international level, the World Meteorological Organization and the International Council of Scientific Unions have joined to plan a World Climate Research Program encompassing the two decades 1980-2000. Its main objectives are:

1. To improve man's knowledge of the natural variability of climate.
2. To understand the responsible causes and mechanisms.
3. To assess the impact of natural and man-made climatic perturbations.
4. To develop techniques for predicting future climate changes.
5. To help in planning courses of action that reduce the effects of possible future adverse climatic changes.

An essential element of the World Climate Research Program and any climatic study is the availability of suitable climatic observations. Observations that are available at this time can be separated into two categories: conventional (standardized) observations and contemporary measurements. Measurements of meteorological variables that are standardized in nature have been made in various regions of the world for about 100 years. In Europe, instrument records dating back to the mid-seventeenth century exist but most are difficult to interpret. These measurements which are adding to already existing data

bases are extremely important but are not sufficient by themselves to meet the requirements of a well organized climate research program. A second category of climatological measurements has recently evolved which includes measurements in regions previously inaccessible to technology and measurements of climatic parameters that could not be made with previously existing techniques. This category of measurements is made possible mainly by recent advances in the technology of utilizing satellites as the measuring platform. For example the globe can now be blanketed with various measurements to yield synoptic views of the earth and its atmospheric covering never before possible. The Global Weather Experiment, part of the Global Atmospheric Research Program of the World Meteorological Organization and the International Council of Scientific Unions, is typical of this new technology where five geostationary satellites supplemented by two polar-orbiting satellites will be used to gather global data while aircraft and ships gather data in the tropical and southern hemispheric oceans away from conventional measurements on land. It is this coverage of the world's oceans and previously inaccessible areas by satellites that shows the greatest promise for substantially increasing our knowledge of the climate.

The importance of the oceans to climate is still not fully realized but research in the past few years indicates that their involvement is significant. In the following section, a review of the interlinkages of the oceans with the atmosphere and hence climate will be presented. A distinction is made between the ice-free oceans (the hydrosphere), and the ice-covered oceans and continental ice sheets (the cryosphere) because of the different roles each play in the climate. The remainder of this document will address the demonstrated and expected capabilities of a proven satellite instrument, the radar altimeter, for providing a unique set of geophysical measurements pertinent to investigations of these hydrosphere/cryosphere/atmosphere interlinkages.

THE ROLE OF THE HYDROSPHERE IN CLIMATE

It is necessary to begin with a definition for climate. No universal definition exists but it is commonly defined to be the state of the atmosphere averaged over an appropriate time span. What, then, is the role of the oceans in global climate?

A review of the average circulation, or general circulation, of the atmosphere is a convenient topic to begin the discussion. If the earth is in thermodynamic equilibrium, then the net solar radiation absorbed by the earth-atmosphere system must equal the amount of long-wave, or infrared, energy radiated back into space by the planet. Because of the curvature of the earth, the distribution of solar energy impinging on the system is latitude-dependent, with a maximum at the equator and a minimum at the poles. In con-

trast, the earth radiates as a sphere rather than as a disk causing there to be little latitude-dependency in its infrared radiation characteristics. The combination of the two radiation budgets creates a radiation excess in the tropics and a deficit in the polar areas. The gradient builds a pole-to-equator temperature difference and therefore a store of available potential energy ready for release by some mechanism.

Travelling waves encircling the globe in the mid-latitudes are that mechanism. Cyclones and anticyclones, the manifestations of these waves at the earth's surface, are the main means for transporting energy from the equator towards the poles in the atmosphere. Dominated by the effects of the earth's rotation, these large, or synoptic, scale eddies convert the stored potential energy into kinetic energy, which must balance the energy lost to frictional dissipation, both at the surface and within the atmosphere. They also tend to redistribute angular momentum, causing the predominance of westerly winds in mid-latitudes and easterlies elsewhere.

While the general circulation of the atmosphere is relatively well-known, the average characteristics of the oceans are not. Much of the problem of understanding the oceans' thermodynamic and dynamic behavior stems from our lack of knowledge of the air-sea interface, the boundary at which the two massive fluid bodies, the atmosphere and the oceans, meet. The atmosphere is in direct contact with the oceans over 72 percent of the earth's surface and if it is subject to bottom boundary condition effects at all, then it must respond to oceanic changes that occur. Correspondingly, the atmosphere certainly can affect the ocean conditions as well. It is the physical appearance of the ocean's surface, as it is formed from the combined effects of the atmosphere and the ocean, that can be sensed by satellite radar altimetry. The remainder of this section will contain synopses of those ocean features of climatic importance that are manifested in some way at the surface and can be measured in a quantitative fashion by satellite radar altimetry.

Passive Heat Storage

The short-wave energy impinging on the earth-atmosphere system reaches the ocean's surface both as direct and indirect, or scattered, radiation. Estimates indicate that about half of the energy on the top of the atmosphere reaches the surface. The incident radiation, concentrated in the visible wavelengths, is able to penetrate many meters into the clear tropical oceans. On the other hand, the infrared emissions by the oceans occur only from the top few millimeters because of the opacity of the water to the long-wave radiation. Hence, there is a net storage of energy in the tropical oceans and a pole-to-equator gradient in stored available potential energy and temperature similar to the situation with the atmosphere. A net balance is reached by the advection of stored energy away from the equator by ocean currents, by the transfer of sensible heat from the ocean's

surface to the atmosphere by turbulence and by the cooling of the surface by evaporation. Within the ocean's vertical column, convection and/or mixing are responsible for the transport of energy to the surface from the depth at which it was originally stored.

In contrast to the equatorial situation, in the mid-latitudes the storage of radiative energy as heat in the ocean is not constant throughout the year but is dependent upon the season. The storage of heat is a maximum in the middle latitudes of the Northern Hemisphere at the summer solstice and is a minimum at the winter solstice.

The processes of convection and/or mixing in the upper portions of the ocean tend to not only bring stored heat to the surface for redistribution within the energy budget system but also to rather uniformly mix the heat and chemistry characteristics of the sea down to some level called the thermocline. Typically located at a depth of approximately 100 meters, the waters above this boundary layer are warmer, more turbulent, and more saline. In middle latitudes, a second, summer thermocline is found atop the main thermocline. It is the result of the seasonally varying excess and deficit of stored radiative energy. The heat stored in these mixed layers is returned to the atmosphere when cold winter air moving off the continents comes in contact with the warmer upper layer of the ocean. By the combined effects of evaporation and the direct transfer of sensible heat, the atmosphere is warmed. The beneficiaries of this warming are the lands on the eastern boundaries of the midlatitude oceans, such as England and British Columbia. Estimates are that European winters would be considerably milder than those of eastern Canada even if there were no major ocean currents. The heat stored in the ocean layer above the summer thermocline is sufficient to account for this difference. Thus, measurement of the amount of stored heat and the depth of the thermocline on a global basis is crucial.

Active Heat Transport: The Ocean Currents

The surplus of energy stored in the tropical oceans must be redistributed throughout the oceans just as the net excess of radiative energy in the atmosphere is redistributed by the waves in the general circulation of the atmosphere. There are several known active mechanisms which produce this energy redistribution in the oceans. The well-known postulation is that warm water currents such as the Gulf Stream carry heat poleward, as cold currents on the eastern edges of the ocean basins transport cooler water to the equatorial regions. Spinning off from these major currents and their energetic meanders are mesoscale eddies that also have significant heat-carrying capacities. A final hypothesis concerns the sinking of northward-flowing warm surface waters. At high latitudes, these waters are cooled by the heat deficit in the earth-atmosphere system and hence sink. If returned to the equator along the ocean's bottom, then the net transfer of heat for the sea is poleward. As of now, determination of the relative importance of this last

mechanism of heat advection in the oceans is incomplete. However, there is no doubt that global circulation and changes in the circulation patterns have a large effect in the local climate of certain areas of the world. Thus complete knowledge of the global circulation and transport is required for climate studies.

THE ROLE OF THE CRYOSPHERE IN CLIMATE

A key indicator of the global heat balance is the amount of ice present in the polar region. Within the past generation, significant changes in the extent of glaciers have been observed indicating that our climate is somewhat warmer now than it was several decades ago. From year-to-year, the boundaries of the sea ice surrounding Antarctica and the southern boundary of sea ice in the Arctic serve as indices of the severity of the winters. Knowledge of the thickness of the ice sheets atop Greenland and Antarctica and the rate of change would be solid evidence of climatic change.

Beyond the importance of ice as an indicator, however, is its importance in the climate itself. A by-product of the earth's heat balance, the cryosphere is an integral part of that balance. If the atmosphere and earth were to cool for any reason, then it can be hypothesized that the extent or percentage of the earth covered by ice would increase. In contrast to ocean water, which has a reflectance or albedo of some 10-15 percent, the ice reflects 50 percent of the incoming solar radiation to space, and nearly 80 percent if it is snow-covered. This large differential in the amount of energy reflected by the earth's surface may be manifested as a further decrease in the temperature of the earth-atmosphere system and a reinforcement of the original temperature perturbation. This hypothesis describes a positive feedback mechanism that is the major feature of simplified models of the climate. Some have shown that a decrease in the solar radiation flux of 2 percent would be sufficient to cover the globe with ice because of the radiation/albedo/ice feedback mechanism. The validity of the results of such models is still to be determined but the critical role of ice in the climate is well-known and accepted. The importance of accurate determinations of the boundaries of sea ice and the thickness of the polar ice sheets cannot be underestimated.

HYDROSPHERE/CRYOSPHERE/ATMOSPHERE LINKAGE

The phrase "teleconnections" has recently been used to describe the apparent ties between such climate features as El Nino, cold winters in the United States and Europe,

the weakening of the Indian monsoon, drought in the Sahel portion of Africa, and unusually intense hurricane activity in the Pacific. This relationship has been observed during the years of El Nino events including 1891, 1925, 1941, 1957-58, 1965, 1972-73, and 1976.

El Nino is a massive incursion of abnormally warm water into the coastal waters off Peru and Ecuador, where the upwelling of nutrient-rich cold water is expected. Wyrtki (1977) has offered an explanation for this event using sea level records from island and coastal sites in the Pacific. Preceding the onset of an El Nino event, the prevailing southeast tradewinds are strengthened to the degree that water is displaced towards the west thereby creating an increased volume of mixed layer water in the Central Pacific. The actual event is triggered by a collapse in this wind flow causing a sea level relaxation. An internal wave, trapped at the equator, then propagates to the east, raising the thermocline in the Central Pacific and lowering it in the east. The existing currents in the region are re-routed towards the south rather than towards the west and north as is normal.

In these climate teleconnections are imbedded economic and commercial implications. If El Nino is triggered, then the fishing industries of Peru and Ecuador are severely hurt causing a scarcity of fertilizer for the world's farmers. Cold winters in the United States and Europe impact agriculture and the cattle industry as well as fuel consumption. The colder temperatures increase the amount of open ocean covered by sea ice causing a reduction in the commercial shipping in these regions. A weakened Indian monsoon and a shifting of the Intertropical Convergence Zone south of its normal position create drought conditions on the sub-continent and in the African Sahel, respectively, threatening the lives and livelihoods of the impoverished inhabitants.

Are these linked? No one knows yet although the correlation has been shown to exist. If concrete proof existed that there is a cause-and-effect relationship between characteristics of the oceans, the world's sea ice and ice sheets, and the atmosphere, then predictive climate modelling could be developed for forecasting climate fluctuations. Preparations for coping with climatic variations could minimize their influence on economics and natural resource allocations. Hence, there is a great deal of justification for making as many climate measurements as possible of hydrosphere and cryosphere variables at the same time. Then changes in the value of one climate variable may be associated with changes in the value of another.

SUMMARY OF SIGNIFICANT OCEAN AND ICE MEASUREMENT NEEDS FOR CLIMATE STUDIES

From these preceding discussions, the following measurements can be selected as crucial requirements for studies of the earth's climate.

- The amount of passive heat storage in the oceans can be determined from surface temperature measurements coupled with measurements of the thermocline depth on a global basis.
- The amount of heat transported by the ocean's major current systems can be determined by coupling surface temperature measurements with measurements of the current boundaries and the velocity of the flow.
- Accurate measurements of the location of sea ice boundaries in polar regions and of the thickness of ice sheets in Greenland and Antarctica are needed as indicators of climatic change and for determinations of the effective albedo of the earth-atmosphere system.

These measurements should be made in conjunction so that variations can be correlated to deduce the presence or absence of "teleconnections."

SATELLITE ALTIMETRY

It will be shown in the rest of this paper that satellite radar altimetry is capable of providing these needed measurements for climate studies. The radar altimeter is an instrument that is conceptually simple in design. Originally conceived to produce measurements of the ocean geoid which is the equipotential surface assumed by the ocean in the absence of dynamic effects such as currents, tides, and surges, the altimeter has been the subject of a considerable body of work in the literature. However, few of the previous altimeter papers have dealt with the full range of capabilities of the instrument. This paper is written to propose the application of an existing radar altimetry technology to the new field of climate research that can utilize the totality of the instrument's measurement capability. Much of the altimeter literature is too narrow in scope and will not be reviewed here. Articles by Miller and Hammond (1972), McGoogan (1975), and McGoogan and Walsh (1978) do, however, address the multi-faceted capabilities of radar altimetry and serve to map the increase in our knowledge of these capabilities through the SKYLAB and GEOS-3 altimeter experiments.

A brief discussion of the satellite radar altimeter's operation follows. From its position within a near-circular orbit around the earth, a narrow pulse is transmitted in the direction of the nadir. Propagating downwards through the atmosphere, the pulse reaches the surface after some elapsed time and is reflected by that surface back towards the satellite altimeter receiver. Measurement of the total time required for the two-way transmission of the pulse results in a determination of the distance between the satellite and the surface, given the velocity of electromagnetic energy propagation. By determining the satellite's orbital position with land-based tracking systems, the height of mean sea

level in ocean regions is determined if there are no dynamic ocean features disturbing mean sea level such as currents, tides, and surges.

Figure 1 shows the typical shapes of the signals involved in altimetry measurements. The transmitted pulse is on the left and the waveform received at the altimeter receiver some time τ later is on the right. The elapsed time is counted for each transmitted pulse. Electronic gates positioned in time approximately at the delay expected, given the satellite's altitude, are used to detect changes in the mean distance from the altimeter to the mean sea surface. Then corrections are made by an electronic feedback loop to reposition the gates to the appropriate delay for the next transmitted pulse. The elapsed time from the time of transmission to the time of the appropriate new gate position is then used to calculate the new altitude. In this way, the gates always "see" the reflected pulse shape shown in Figure 1 modified by the effect of the noise or jitter introduced by the positioning process. SKYLAB, GEOS-3, and SEASAT have utilized different numbers of gates to sample the return waveform. The greater the number, the better the shape of the waveform can be determined.

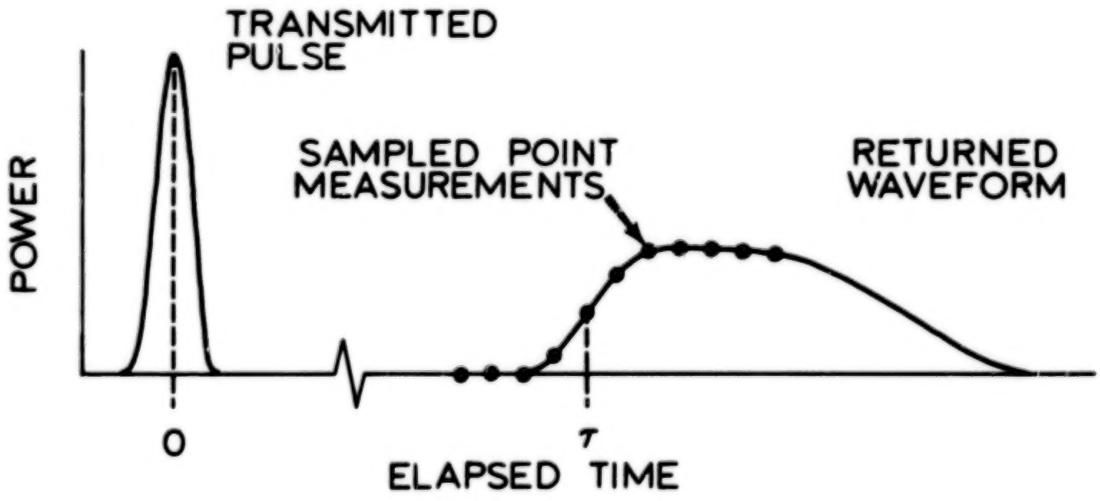

Figure 1. Typical altimeter transmitted pulse and returned waveform.

The shape contains considerable information about the nature of the surface that reflected the altimeter's transmitted pulse. If the surface is smooth, then it is highly reflective of the microwave energy, and the leading edge of the return waveform will rise sharply as the spherically - expanding pulse impinges on the surface. The circular area illuminated by the pulse will increase until the back of the pulse arrives at the surface. Thereafter, an annulus of constant area but increasing diameter and narrowing thickness is illuminated. Once the circle at the nadir is filled, the power of the return signal is constant for some time until it eventually decays with elapsed time as the limits of the

antenna beam width are reached and scattering by the surface of energy out of the instrument's receiver's look angle becomes significant.

If the surface has large scale roughness then the crests are illuminated prior to the time/position of the mean surface. Equivalently, the troughs are not illuminated until after the normal time/position of the mean surface. The presence of ocean waves thus decreases the slope of the leading edge of the return pulse waveform. The number of reflective facets per unit of surface area oriented in the direction of the altimeter receiver affects the strength of the backscattered signal. In the limiting case of the smooth surface, not only is the slope of the leading edge very steep but the duration of the backscattered waveform is very short. Once the transmitted pulse spreads out on the surface away from the satellite's nadir, the facets of a smooth surface are oriented such that reflection out of the antenna beamwidth occurs. Correspondingly, for a rough surface, reflection into the beamwidth takes place for a considerable time after the surface is first illuminated. Processing of the stored electronic gate point measurements makes it possible to differentiate between surfaces of differing roughness and to quantitatively measure the large scale surface roughness.

In summary, satellite radar altimeter data contains information about the mean sea surface height, the roughness of the surface, and the reflectivity of the surface. These three measurements, when suitably analyzed, are able to satisfy the needs for climate research discussed previously. In the following section, the analysis techniques that have already been developed and proven will be presented. The applicability of existing radar altimetry data products to climate research will be stressed, and an extensive list of references dealing with climate-related applications of radar altimetry will be presented.

DESCRIPTION OF EXISTING CLIMATE-RELATED ALTIMETER DATA PRODUCTS

Ocean Current Boundary Determination and Velocity Measurements

Although attempted with the data from SKYLAB, the detection of ocean currents from satellite radar altimeter data was not successful until the GEOS-3 instrument was placed in orbit. Development of the data analysis techniques capable of recognizing the signature of a major current such as the Gulf Stream in altimeter sea surface height data has been the result of the efforts of Leitao, Huang, and Parra (Leitao, Huang, and Parra, 1978a; Huang, Leitao, and Parra, 1978; Leitao, Huang, and Parra, 1978b; Leitao, Huang, and Parra, 1978c).

Because large-scale ocean dynamics are geostrophic in nature, it is necessary only to measure accurately the tilt or slope of the water's surface across a current to determine its velocity and its position (Fofonoff, 1962). Problems of data editing and smoothing have been resolved by Leitao et al. The key to the success of these techniques is the availability of high resolution gravimetric geoid data. With the position of the satellite above a reference spheroid known from orbital computations and the departure of the marine geoid from this spheroid known from the gravimetric geoid, then any residual heights measured by the altimeter are due to dynamic effects. If the gravimetric geoid is in error or too coarse in resolution, then erroneous or misleading dynamic topography is calculated. In the region of the Gulf Stream, Leitao, et al. have relied upon the 5' x 5' geoid computed by Marsh and Vincent (1975). Elsewhere, gravimetric geoid data is not satisfactory at this time for these techniques to be applicable. The success of these methods is remarkable. The ability to locate the Gulf Stream boundaries is illustrated in Figure 2. Over a meter of height difference in mean sea level is seen to exist between slope and shelf water shoreward of the Gulf Stream and Sargasso sea water seaward of the

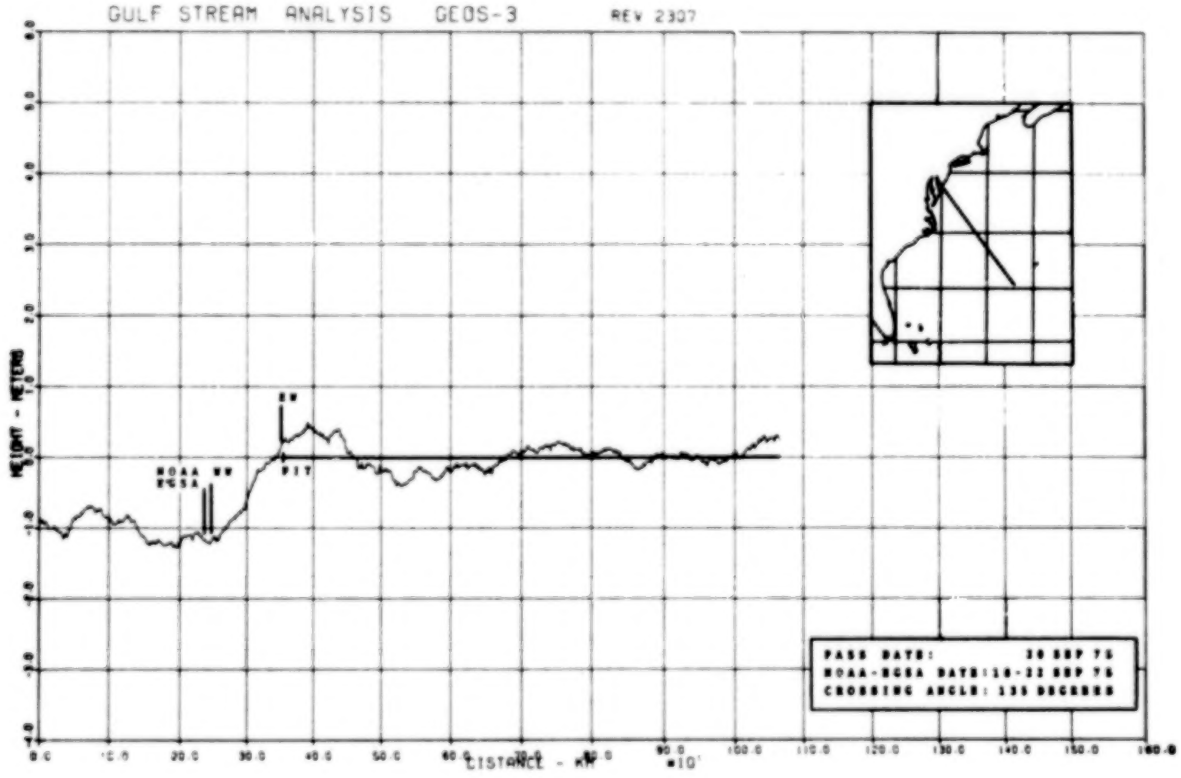

Figure 2. Single pass sea surface height profile from GEOS-3 indicating the Gulf Stream's eastern (EW) and western (WW) boundaries as determined by the radar altimeter and the western boundary as estimated by NOAA-ESSA (Leitao, Huang, and Parra, 1978b).

current. The eastern and western walls of the current are defined by the break points in the height profile. The agreement with the Experimental Gulf Stream Analysis (EGSA) western wall position produced by the NOAA National Environmental Satellite Service is good. This agreement is consistent. Discrepancies when found are due to the influence of cloud cover on the infrared imagery used by NOAA in the EGSA determinations and to the displacement of warm surface waters from the axis of the Gulf Stream's flow by the boundary layer wind field.

Using the equation for geostrophic flow, the velocity of the flow is computed by Leitao et al for measured slopes across the current. In Figure 3, the dynamic topography and computed velocity profiles for three GEOS-3 altimeter passes over the same groundtrack are displayed. Not only are the three data sets in good agreement, but during the three month span between the first and the last, the velocity diminished in accord with published reports of mean flow variations (Fuglister, 1951).

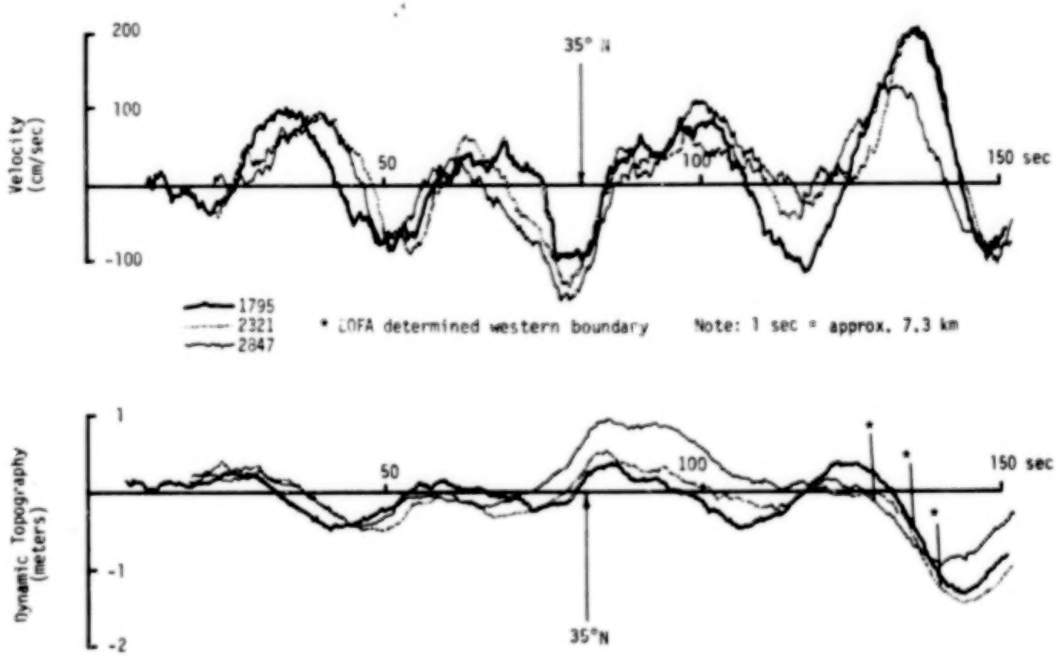

Figure 3. Comparison of dynamic topography and current velocity derived from three repeated altimeter profiles acquired over the same groundtrack during three successive months (Leitao, Huang, and Parra, 1978b).

Leitao et al have also extended their analyses to include Gulf Stream rings, eddies that are spun off from meanders in the current itself. Figure 4 shows the movement of a particular ring as measured by infrared and radar altimeter instruments. Clearly, the altimeter is capable of determining the location of major ocean currents, their flow velocities, and the physical size, strength, and trajectories of eddies generated by the currents.

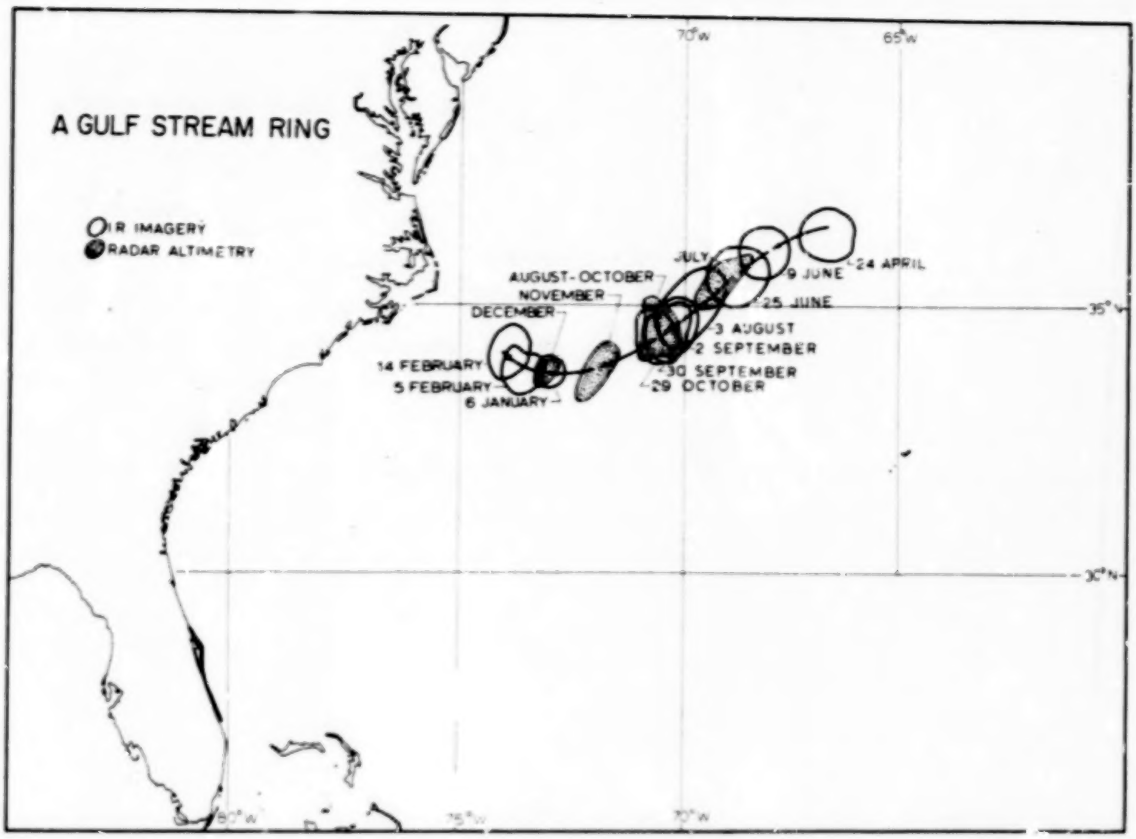

Figure 4. Gulf Stream ring movement sequence as defined from infrared imagery and satellite radar altimeter data (Huang, Leitao, and Parra, 1978).

The all-weather seeing capability is a positive feature of altimetry for this and all applications. The major impediment between present-day altimetry and a role in climate study programs in the future is its dependence upon high resolution gravimetric geoid data. This can be overcome in the following fashion. Using the large altimeter data bases established by GEOS-3 and SEASAT, the mean ocean surface topography can be determined globally (Brace, 1977). This includes not only the gravimetric geoid but also a contribution by those ocean dynamics features that are permanent fixtures in the ocean such as the major currents. Features that move with time such as the Gulf Stream rings or that last only a finite period of time will not be present in the mean surface topography map because of the averaging of repetitive passes over the same geographic location separated by significant intervals of time. If the effect of the mean current flow on dynamic topography is known from hydrographic data being collected now at depositions such as the Woods Hole Oceanographic Institute and the World Oceanographic Data Center, then it can be subtracted from the altimeter-determined mean surface topography to yield the gravimetric geoid. Then current measurements can be made worldwide using the techniques of Leitao et al to provide an essential data set for climate studies.

Significant Wave Height Measurement

Efforts to quantitatively measure the slope of the leading edge of the pulse returned to the altimeter from the ocean's surface for inferring sea state have recently reached fruition (Walsh et al, 1978; Fedor and Barrick, 1978; Parsons, 1979; Rufenach and Alpers, 1978). Additionally, several papers on this subject have been published in a special issue of the Journal of Geophysical Research (Vol. 84, No. B8, July 30, 1979) dedicated to GEOS-3 results. A summary of the various algorithms in existence for measuring this slope for use in calculating the significant wave height (SWH) of deep ocean waves (Fedor et al, 1979) is also included. A convention among radio oceanographers, SWH is defined to be four times the standard deviation of the wave height distribution assuming that deviations from mean sea level caused by the waves are distributed normally about mean sea level. The validity of this assumption will be discussed later in this paper. Fedor et al (1979) conclude that all algorithms tested produce answers in close agreement to available ground truth measurements and in good agreement with each other. One technique produces results within thirty minutes of data collection portending a global real-time sea state measurement capability.

A disturbed sea surface is a very transient ocean feature lasting a few days to two weeks at most. On this time scale it is intimately tied to its cause, the weather, but not to the mean weather conditions, the climate. Sea state is the dominant mechanism for transferring momentum and mass across the air-sea interface from the boundary layer wind field above to the upper ocean layer below. Knowledge of the mean sea state on a global basis must be an essential element in climate studies.

Although radar altimeters are nadir-pointed instruments that illuminate only narrow swaths along their groundtracks, Parsons (1979) has shown that contour maps of SWH can be produced from GEOS-3 data that compare favorably with other sea state maps currently in operational use. Figure 5 is an example of the product that is available using existing technology and techniques. This map was constructed with GEOS-3 data collected on February 24, 1976, in the North Atlantic. The contour spacing is 1 m. The major problem with the production of SWH maps from GEOS-3, the loss of coverage caused by the narrow swath width and the limited number of orbits over an area per day, may be cured if advanced altimeter engineering designs are put into practice in the future. These are discussed in a later section.

Surface Windspeed Measurement

By utilizing gate measurements of backscattered signal strength positioned in the plateau region of the return waveform, the radar backscattering cross section per unit

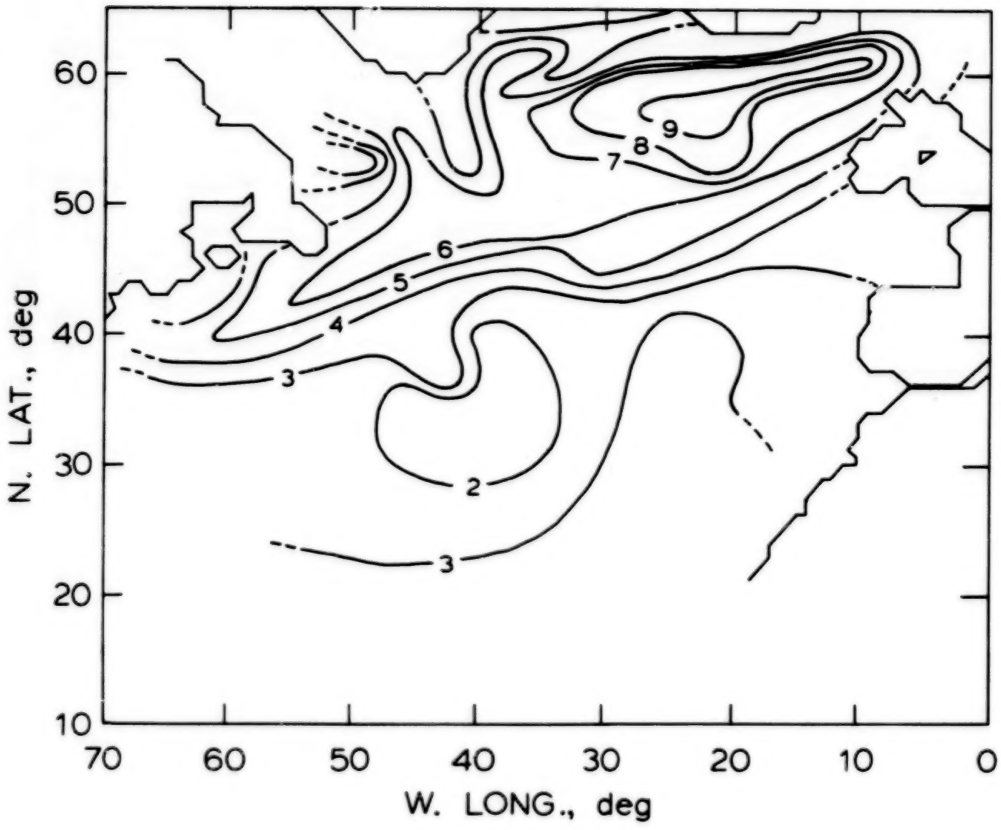

Figure 5. A typical contour map of significant wave height constructed from GEOS-3 radar altimeter measurements. The contour interval is 1 m. This data set was collected February 24, 1976.

area, σ_0, of the sea surface can be inferred. For a nadir-pointing instrument, the determination of $\sigma_0(0°)$ depends upon the antenna pattern, the pointing angle of the antenna boresight relative to nadir, the transmitted pulse shape, and receiver effects to correct these gate measurements. Brown (1977) has shown that $\sigma_0(0°)$ is directly proportional to the normal incidence Fresnel power reflection coefficient of a flat sea surface and inversely proportional to the mean square slope of a low pass filtered replica of the true surface. Furthermore, Cox and Munk (1954) used measurements of the surface mean square slope in the open ocean with and without filtering to show that the mean square slope is proportional to the natural logarithm of the boundary layer windspeed W. With σ_0 known from the corrected gate measurements of signal strength, an inferred value of W can be obtained (Brown, 1978).

Brown (1978) has shown that good agreement exists between altimeter-inferred windspeed and ground truth measurements of W. A precision of ± 2.6 m sec^{-1} was found in a comparison with measurements from ships-in-passage and a value of ± 2.1 m sec^{-1} with National Data Buoy Office (NDBO) measurements. This precision is roughly the same as the granularity in the reports by ships-in-passage and in hindcast estimates of windspeed from pressure gradient analyses. The major assumption in this technique (Brown, 1978) is the requirement that the probability density function for the slopes of the filtered sea surface not be a function of windspeed. From the intercomparisons with ground truth, this does not appear to be a bad assumption.

As is the case for SWH measurements, the major importance of windspeed measurements for climate lies not in data collection over the time range of days to weeks but in the seasonal or yearly mean windspeeds over the entire globe. The major mechanism for transferral of momentum from the atmosphere to the oceans, the average winds are direct indicators of atmospheric energetics. The contour map of windspeed shown in Figure 6 corresponds to the SWH map in Figure 5 (Parsons, unpublished manuscript). It contains isolines of windspeed inferred from the GEOS-3 satellite data spaced at an interval of 10 knots, those ship reports of windspeed and direction available for February 24, 1976, in the North Atlantic and a dashed line indicating the location of the major weather system fronts at 1200 GMT on that day. The ship and satellite data are in good agreement. The fair weather bias is in evidence with only two ship reports available for comparison within the 40 knot contour line.

As is the case for SWH contour mapping, the production of these maps is hindered only by the sparse coverage of the globe resulting from having only a single altimeter in orbit. Radar altimetry is not capable of determining wind direction or wave height propagation direction, but for climate applications these are not important. The mean windspeed and wave height are the measurements of interest.

Sea Ice Boundary Mapping

The contrast in the backscattering properties of smooth sea ice and the rough ocean surface is so great that altimetry has been shown to have a unique all-weather capability for determining the location of the sea ice boundary (Brooks, Roy, and Stanley, 1978; Brooks et al, 1977). The smooth ice reflects microwave energy very efficiently at the nadir. After the pulse begins to spread on the surface, however, the reflected power drops quickly to zero as scattering out of the antenna beamwidth occurs. In contrast, the rougher water continues to reflect energy for an extended time period. By making waveform sampling gate measurements late in the plateau region of the return waveform, a sensitive detector of the sea ice boundary is available using conventional altimetry.

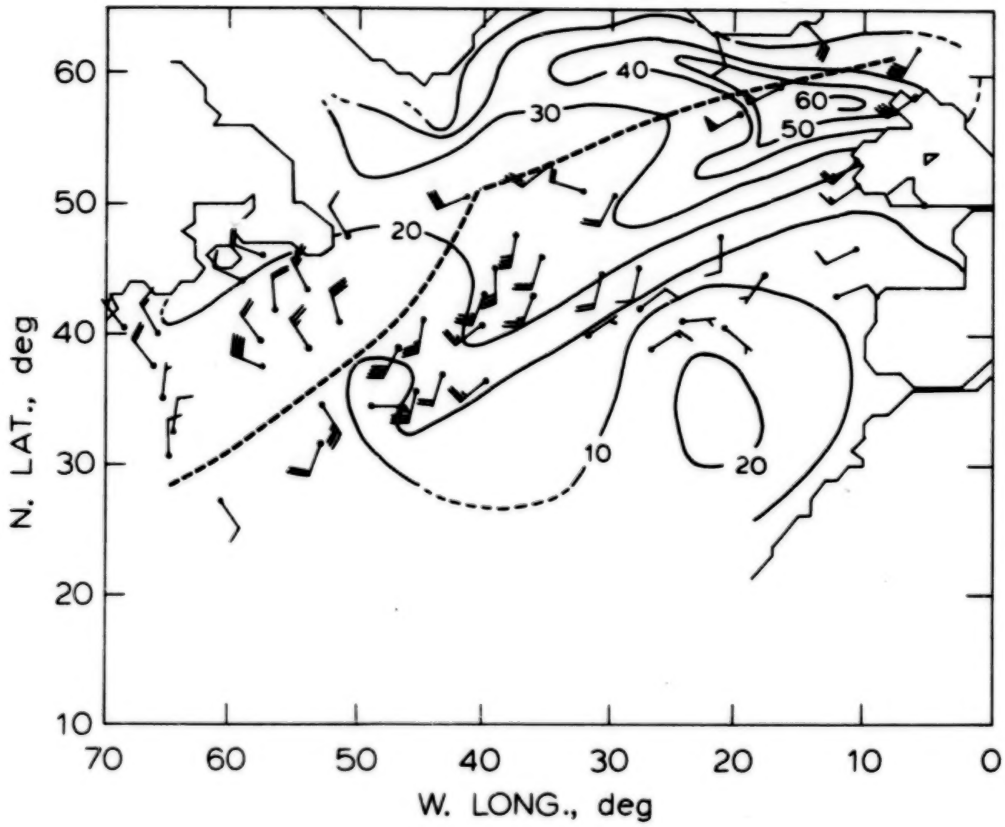

Figure 6. A typical contour map of surface windspeed constructed using GEOS-3 radar altimeter measurements. The contour interval between the solid lines of constant windspeed is 10 knots (1 knot = .575 m sec^{-1}). The dashed line indicates the location of the surface fronts and the plotted ship reports of windspeed are those available for the date of this data set, February 24, 1976.

Figure 7 shows an intercomparison of altimetry-determined sea ice boundaries around a portion of Antarctica with the map produced by the Navy Fleet Weather Facility. Using infrared and visible satellite imagery when available, present techniques can locate the boundary to within ± 30 km of the actual position. Altimetry, because of the high pulse repetition frequency possible, should be capable of finding the boundary to within ± 2 km of the real position. A polar orbiting altimeter could map the Arctic and Antarctic. Again, the major problem with the microwave technique is the narrow swath width and sparse coverage available with a single nadir-looking instrument.

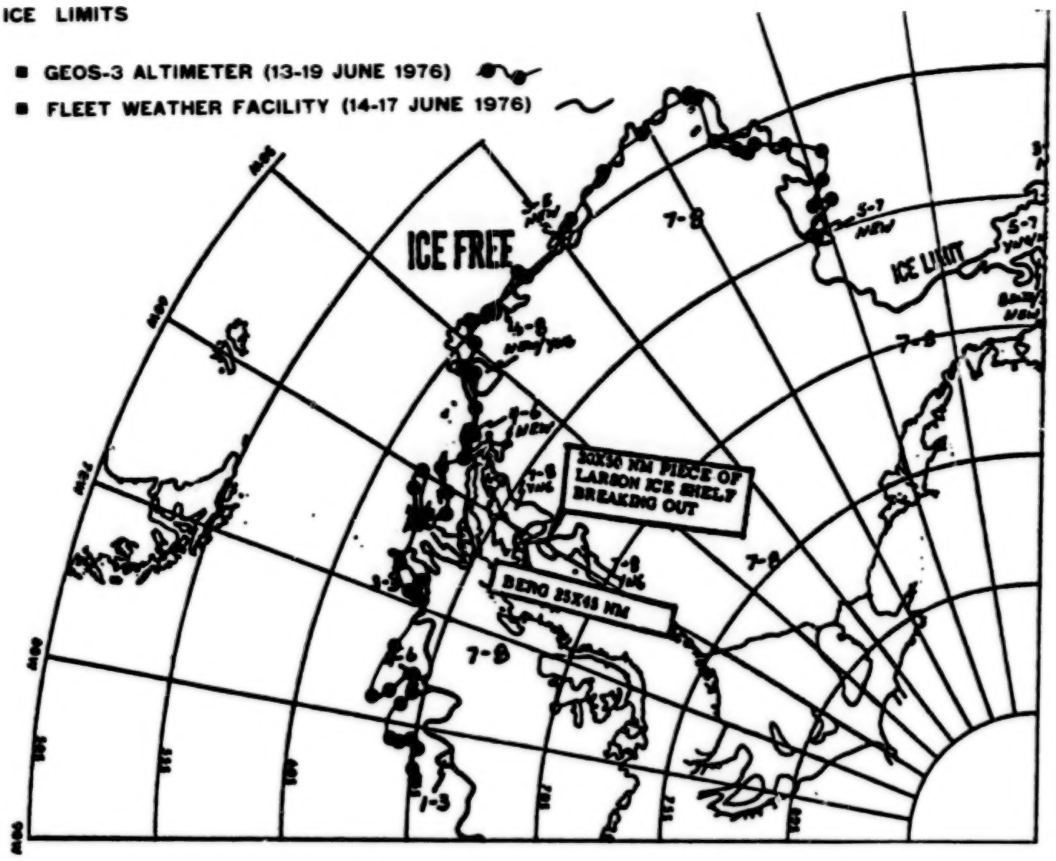

Figure 7. Antarctic sea ice boundary intercomparison.

Ice Sheet Topography Mapping

The last and certainly one of the more important proven capabilities of altimetry is the production of ice sheet topography maps. The volume of water substance that is contained in the Greenland and Antarctica ice sheets is enormous. The sea level equivalent of the Greenland sheet is 6 m and the Antarctica sheet about 60 m. Hence, small changes in their volumes are significant. A change of 1 m in their average elevations would correspond to a change in worldwide sea level of 3 to 4 cm.

As shown in Figure 8, GEOS-3 data has recently been used to produce maps of a portion of the Greenland ice sheet that are clearly superior to the results of any competing technique (Brooks et al, 1978). Although designed for operation over the roughened sea surface, GEOS-3 has demonstrated an ability to also produce profiles over land providing the terrain is sufficiently smooth. In the case of the Greenland ice sheet, the surface is easily tracked except along the coasts, between the ocean and the ice sheet, where mountainous terrain often disrupts the altimeter tracking mechanism. In the Brooks et al

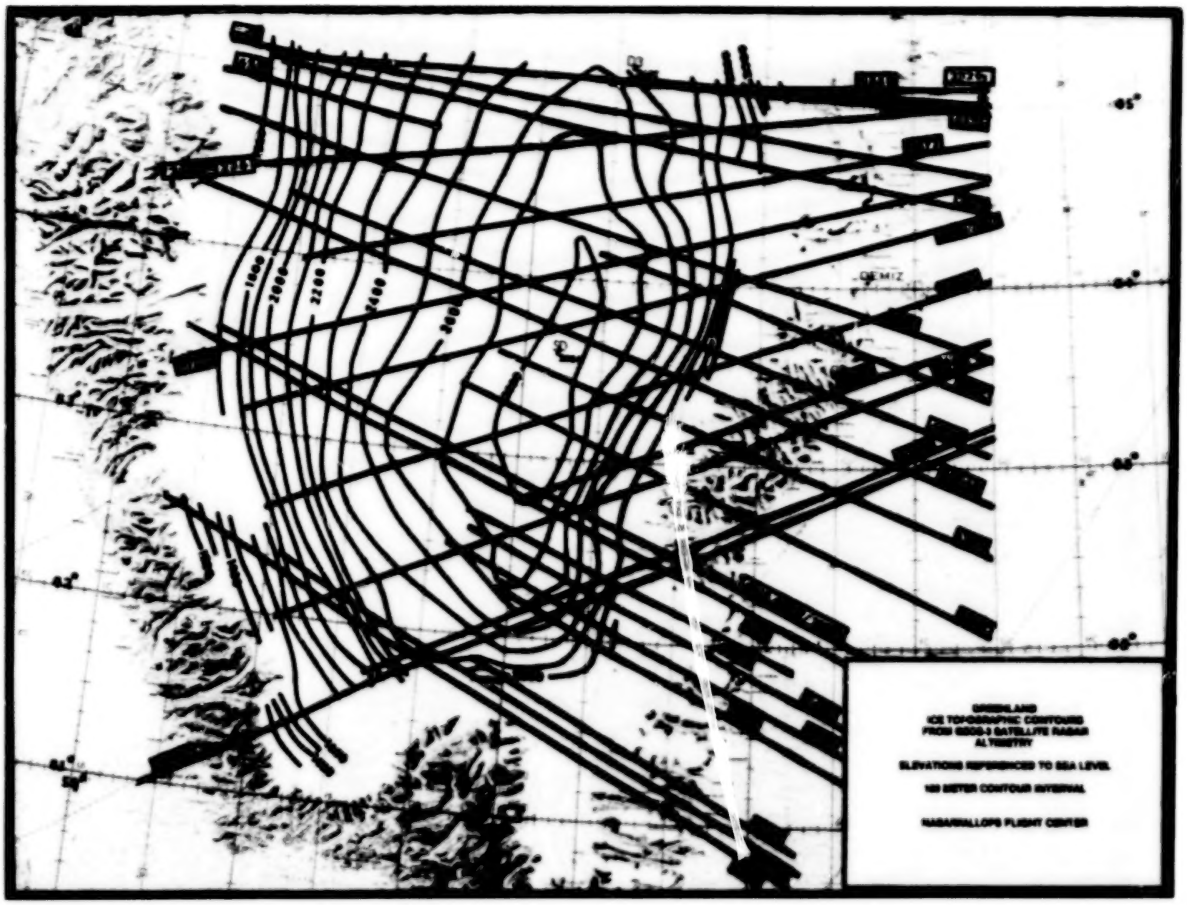

Figure 8. Surface elevation map of southern Greenland ice sheet produced from GEOS-3 radar altimeter measurements. Elevations are referenced to mean sea level, and the contour interval is 100 m (Brooks, et al, 1978).

(1978) study, the altimeter-derived ice surface elevations were demonstrated to have an accuracy of approximately 2 m. This is sufficient to determine a rough estimate of the mass balance between mass input and ice flow if altimeter data is collected in the future for comparison. Surface waves on the ice sheet with a height of 10-20 m and a wavelength of 10 km were also found to corroborate surface measurements and theoretical predictions. In Figure 9, data collected along two parallel GEOS-3 groundtracks separated by .8 km spatially and 16 weeks in time are shown. The mean difference in elevation is well less than 1 m but local differences are as great as 5 m. These are the manifestations of the surface waves oriented in the across-track direction.

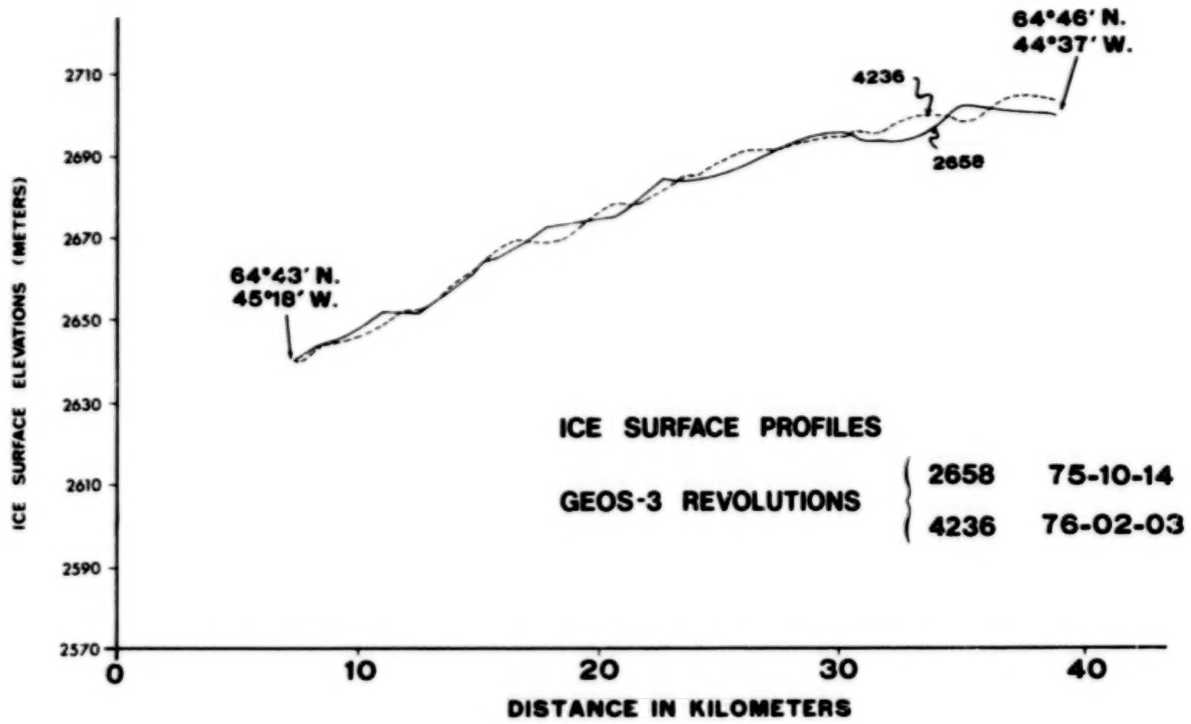

Figure 9. Ice surface elevations on the eastern slope of the Greenland ice sheet along parallel GEOS-3 groundtracks separated by 0.8 km (Brooks, et al, 1978).

In Figure 10, an updated contour map (Zwally and Brooks, 1978) of a smaller portion of the Southern Greenland ice sheet crestline with a contour interval of 10 m is shown. The only accurate determination of altitude in this region prior to GEOS-3 was by Mock (1976) at South Dome. The agreement is good between his measurement of 2824 m and the 10 m resolution contour map. On the western side of the crestline, where no accurate measurements were previously available, the GEOS-3 results give results 100-150 m higher than estimates, indicating an error in previous studies equal to 5% of the ice thickness.

Using the GEOS-3 results, information has been gained about altimeter operation over ice so that the antenna, pulse width, tracking mechanism, and other parameters can in the future be optimized to improve performance. If an altimeter were continually collecting data over the ice sheets, the growth and stability of the sheets could be easily monitored, one of the primary needs in a global climate study.

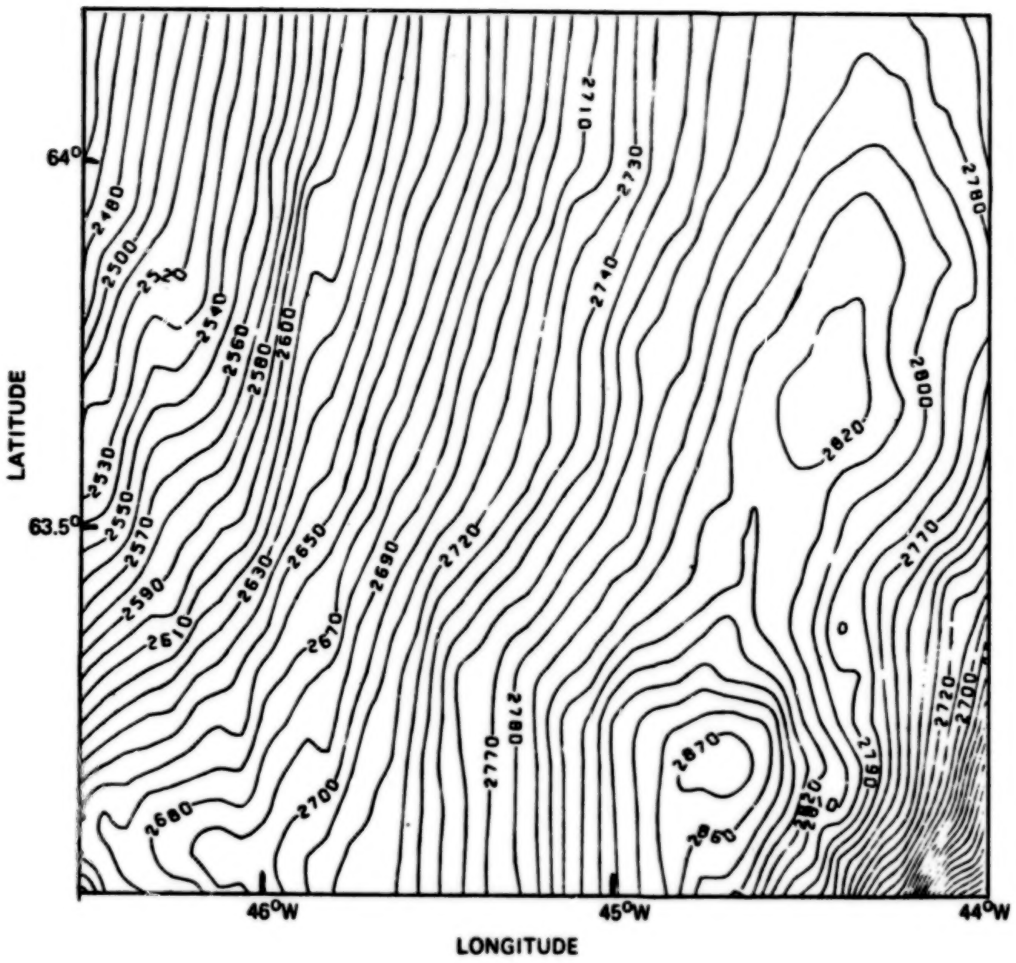

Figure 10. High resolution contour map of Greenland crestline constructed using GEOS-3 altimeter measurements. The contour interval is 10 m.

FUTURE CAPABILITIES

Hardware Improvements

All of the applications discussed above are restricted mainly by the lack of coverage of the ocean or land surface by the nadir-looking, narrow beamwidth altimeters flown on SKYLAB, GEOS-3, and SEASAT. For the topographic mapping of the Greenland ice sheet, the thickness changes of the ice sheet are sufficiently slow that the time involved with waiting for repetitive passes over an area is not detrimental. For other applications,

however, it is highly advantageous to blanket the globe with measurements at a faster rate. Either more satellites must be placed in orbit or an instrument producing multiple beams must be developed to accomplish this objective. The former approach would require no technological advances. The latter approach may be accomplished by two methods. An altimeter with a large antenna could be outfitted with a monopulse feed system to produce multiple beams. Or, a pair of smaller antennas could be oriented in such a way that given the proper phasing, an interferometer pattern could be generated at a desired location off-nadir. The altitude could be recovered unambiguously by proper range gating. Details of these advanced hardware designs are found in McGoogan and Walsh (1978). Studies are underway during the planning stages of the National Oceanographic Satellite System (NOSS) to ascertain the feasibility of building such multiple-beam altimeter systems in the future.

For ice sheet topography applications, the measurement of the along-track and cross-track surface slopes is also desirable. This may also be possible with altimetry. When the surface is nearly horizontal, the large scale surface roughness within the radar footprint can be determined from its stretching effect on the leading edge of the return waveform. This is the case discussed previously, the determination of significant wave height over the ocean. When the surface is tilted sufficiently to distort the waveform, then an analysis such as that done by Walsh (1977) can be used to extract tilt information. The modified shape and range extent of the return waveform are sensitive indicators of total surface tilt. For slopes greater than 4°, the shape becomes more and more symmetrical and its width increases approximately as the sine of the angle. Since the total tilt can be found using the technique described by Walsh (1977) and along-track tilt is known from the topographic profile, then the cross track component can be calculated. An ambiguity in the sign of the cross-track tilt could be resolved by comparisons of orbital data collected over groundtracks in close proximity. Hence, surface tilt determination is feasible using satellite altimetry.

Added Capabilities Resulting from Theoretical and Laboratory Oceanographic Research

It has been shown that present generation satellite radar altimetry is capable of providing many of the measurements needed for incorporating the state or condition of the hydrosphere and cryosphere into climate studies. Significant new applications now appear on the horizon. Advancements in man's knowledge of ocean surface waves have been made on many fronts in the past few years by the team of Huang and Long at NASA Wallops Flight Center. Using state-of-the-art techniques (Long and Huang, 1976), laboratory data have

been produced which when coupled with new theoretical developments is destined to establish a new understanding of surface wave dynamics and energetics.

Much of the work by Huang and Long is as yet unpublished. Therefore, no specific references will be cited but this team is the source of the research results summarized in the following section. First, the new developments in ocean wave theory will be discussed. Then, the applicability of satellite radar altimetry for monitoring additional ocean characteristics pertinent to climate studies using these new theoretical advancements will be discussed.

The key to the work of Huang and Long is their utilization of a new parameter to describe the surface wave field. The significant wave slope, defined as the ratio of the root-mean-square wave height to the wavelength of the energy containing waves, has been found to be the one parameter of the surface waves that can be used to characterize their various properties.

Based upon work by Longuet-Higgins (1969), Huang has derived a theoretical relationship between the significant slope, §, and ω, the energy lost in each cycle by a breaking wave. It is the innovative use of this relationship by Huang and Long studying energy transfer within the ocean mixed layer that produces measurement capabilities crucial to climate studies. Wave breaking has long been known to depend upon the local wave amplitude. Huang and Long have produced wave height probability distributions using the NASA/WFC Wind-Wave-Current Interaction Research Facility tank. By computing the amplitude at which breaking begins to occur using Stokes' instability criterion, the probability can hence be determined that wave breaking is taking place. In the laboratory ω can be computed so that the energy lost per cycle per breaking wave is known. Multiplication by ω of the probability wave breaking occurs yields the total energy lost per cycle, which is the energy dissipation ε.

Phillips (1977) describes the process of entraining turbulence in the ocean mixed layer. The movement of the interface between turbulent and non-turbulent water parcels is a function of the viscosity of the fluid and the mean-square rate of strain near the boundary. The latter is directly proportional to the energy dissipation ε. By expanding this series of arguments in more rigorous fashion, Huang and Long have shown that by knowing § and hence ω, predictions of the movement of the thermocline are possible. This has a tremendous implication for climate research. By measuring a surface wave field parameter, §, the volume of the mixed layer can be inferred.

The radar altimeter is capable of indirectly making this measurement. Detailed analysis by Huang and Long has shown that the Gaussian wave height probability distribution assumption frequently invoked in oceanographic remote sensing studies is invalid, particularly in high wind conditions. It was found that the measured distributions can be accurately modeled by a four-term Gram-Charlier series expansion containing terms involving the moments of the wave generation process statistics and certain Hermite polynomials.

The skewness of the measured distributions was computed and compared with a theoretical expression in terms of the significant slope. Good agreement was found as shown in Figure 11. It is this relationship that can be utilized to link altimetry data to these new developments by Huang and Long.

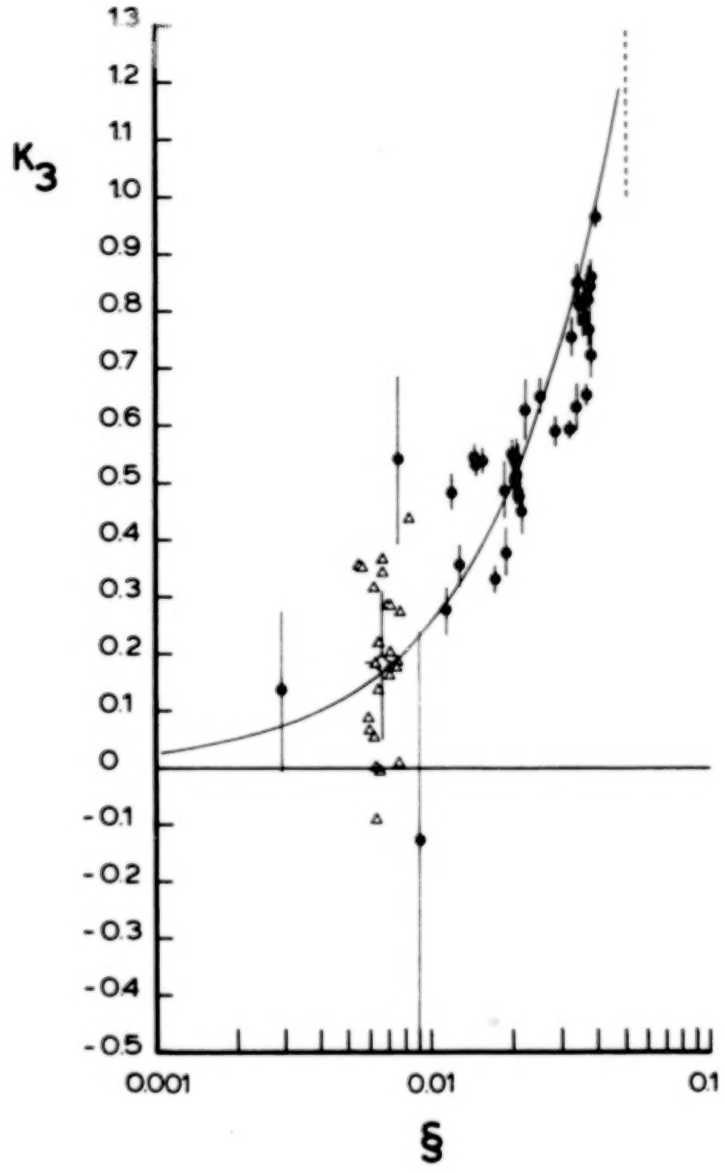

Figure 11. The variation of skewness, K_3, with significant slope, §. The measurements of Huang and Long are denoted by closed circles, the results of Kinsman by the diamond. The theoretical relationship derived by Huang and Long is the solid curve (Huang and Long, unpublished manuscript, 1979).

The generalized altimeter return waveform in Figure 1 can be modeled by the convolution of the wave height distribution, the antenna pattern as a function of the range to mean sea level, the radar point target response, and the range noise in the altimeter tracking circuit. To extract the desired wave height distribution from the shape of the leading edge of the return waveform, iterative methods must be used. The fit between the waveform sampling gate measurements and an analytical functional description of the waveform shape can be judged on the basis of either the sum of the squares of the residuals, the sum of the squares of the residuals normalized by the standard deviation of the averaged observed waveform at each gate, or by a hybrid method. Regardless of the technique used, the functional waveform expression can be expanded to also include a dependence on skewness. When iteratively solving for the parameter values in the expression that maximize the fit with the measured gate data, the skewness parameter value can also be obtained. This was attempted by Walsh (1979) using GEOS-3 data. In Figure 12, the agreement between the computed values of the skewness parameter with those predicted by the results of Huang and Long in Figure 11 are shown. The significant slope was determined by using altimeter measurements of SWH along with values of the dominant wavelength obtained from National Weather Service estimates of wave period. The agreement is quite good especially considering the excessive amount of tracking noise and the large pulse width of the GEOS-3 altimeter. There is considerable flexibility in the design of an altimeter with which the capability of measuring skewness can be optimized. With a skewness measuring capability, the research advances of Huang and Long can be utilized in an operational mode by utilizing the relationship illustrated in Figure 11.

These new results have not yet been proven in the field, but every step of Huang and Long's development is substantiated with laboratory measurements. In view of the potential impact, a field expedition to gather hydrographic data in conjunction with aircraft radar altimeter overflights should be conducted as soon as possible to confirm the validity of this technique.

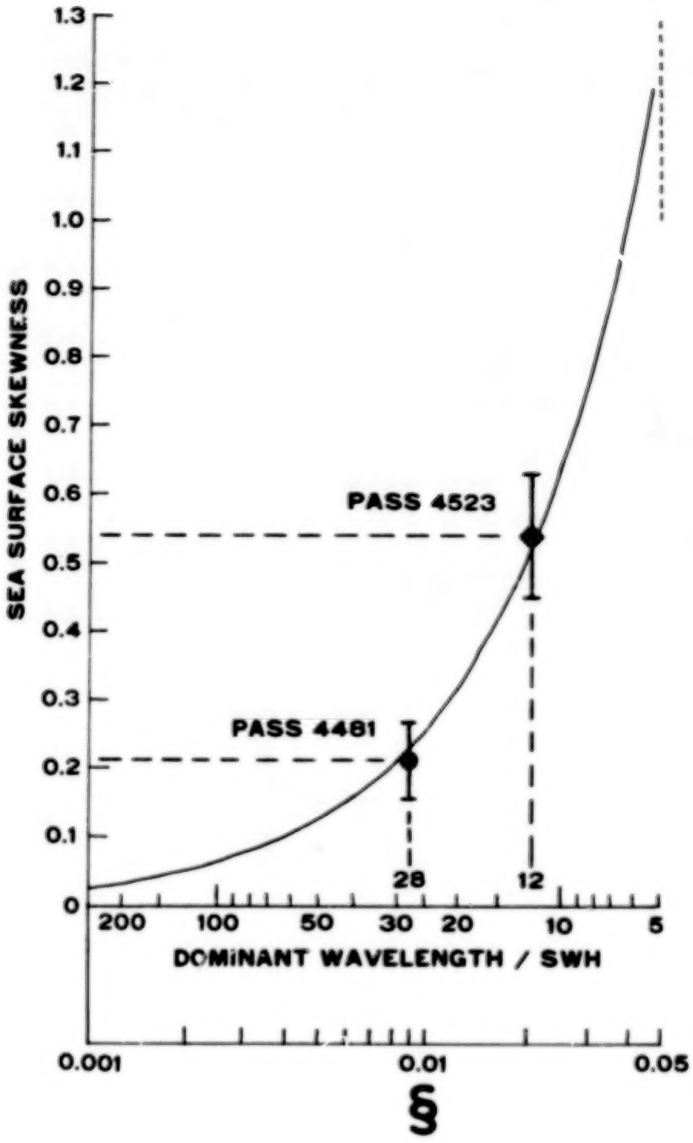

Figure 12. The comparison of skewness values measured by the GEOS-3 radar altimeter with the theoretical curve from Huang and Long as a function of significant slope (Walsh, 1979).

CONCLUSIONS

The radar altimeter has been shown in this review paper to be uniquely qualified to make the critical oceanic and ice measurements needed for climate studies presently underway or planned for the future. In Figure 13, the climate measurements possible with a radar altimeter are summarized. This mixture of diverse measurements is unique to the altimeter. No other existing device has the promise for routinely monitoring currents, ice cover, sea state, and mixed layer depth.

Additionally, the radar altimeter has been shown to have potential for detecting connections between climate features if they exist. With a capability for monitoring the thermocline's vertical displacement, ocean current displacements may be studied and even detected several months in advance of their movements. Coupled with surface temperature measurements from existing satellite instrumentation, the altimeter's current detection and velocity measurement capabilities should be able to monitor any anomalous heat transport associated with the dynamics of the ocean. Do these displacements alter the global ocean heat storage and transport? This question may be answerable using satellite altimeter data.

Using its sensitivity to sea ice boundary reflectivity changes, the altimeter can map the extent of the sea ice on a day-to-day basis. Annual differences that have occurred during certain years can be measured and possibly linked to oceanic heat transport and storage differences. Variations in ice sheet thickness from year-to-year can be monitored for Greenland and Antarctica. Monthly or seasonally averaged windspeed and significant wave height statistics can be determined to describe variations in the atmospheric circulation. The diversity of this instrument's proven capabilities and its promise for the future demand that radar altimetry be given a central role in climate studies.

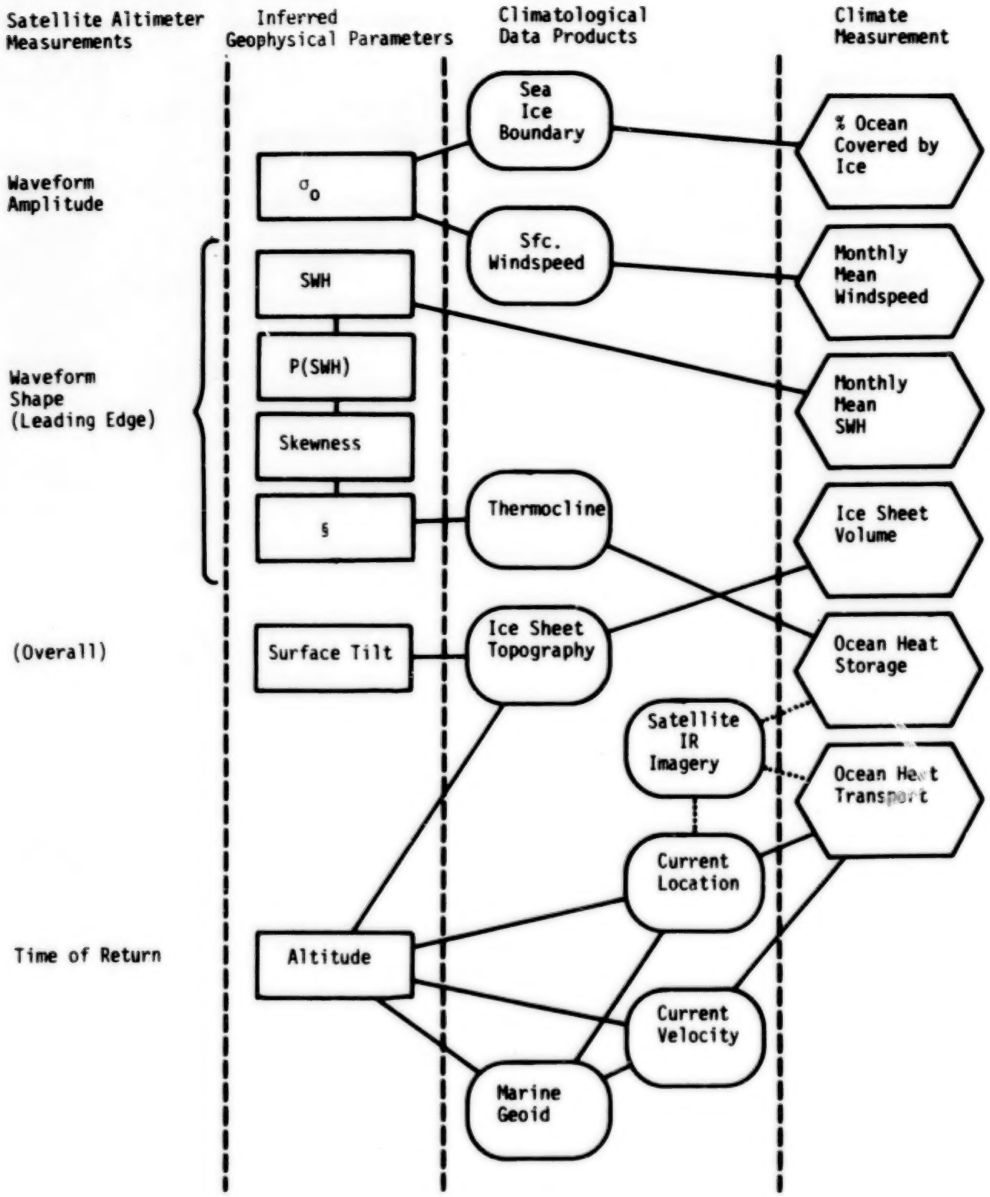

Figure 13. Satellite radar altimeter climate data flow.

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15. Supplementary Notes

16. Abstract

The results of three generations of satellite-borne radar altimetry experiments are summarized. The diverse measurements possible from this instrument are shown to be directly applicable to studies of the importance of the oceans in climate. The radar altimeter has unique value for investigations seeking knowledge of the interconnections between ocean dynamics, heat and momentum transfer across the air-sea interface, sea ice extent, and polar ice sheet thickness.

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